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ELSA AND THE FRONTIERS OF ASTROMETRY

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Abstract. ELSA stands for the ambitious goal of ‘European Leadership in Space Astrometry’. In this closing contribution I will examine how the ELSA network has advanced this goal. I also look ahead to the time when the Gaia data will be published and consider what needs to be done to maintain European leadership.

1 Impact of ELSA

First, what does it take to establish and maintain a leadership position in the field of space astrometry? I believe the following ingredients are important. The basic condition is of course to have a wide scientific community interested in the data that can be obtained from dedicated astrometric surveys. The interest should not just be in the classical applications of astrometry (i.e., catalogues of star positions) but in pushing the limits of achievable astrometric, photometric and radial velocity accuracies in order to expand our horizons and learn more about our universe. This strong scientific interest should be complemented by an expert community of astronomers capable of designing and delivering missions such as Gaia. Because of the nature of space astrometric missions, in terms of hardware (spacecraft and payload design) and software (data processing), these experts should welcome contributions from the fields of engineering, mathematics, and nowadays, computer science. The third important ingredient is the existence of competent industrial partners capable of delivering the very complex satellites required for space astrometry. Finally, it is crucial that there are good contacts between these three communities. The scientific users of the space astrometric survey have to understand the limitations of what can be achieved, while the space astrometry experts should not work in isolation but be motivated by the science that will be done with the data they produce. The latter will also very much facilitate the transmission of scientific requirements to ESA and its industrial partners.

The existence of a scientific community in Europe interested in space astrometry is aptly demonstrated by the numerous contributions to this volume, covering

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a broad range of science topics, that show the eager anticipation of the Gaia data. The long astrometry tradition in Europe combined with the efforts to realize the Hipparcos mission have led to a world leading community of space astrometry experts. The Hipparcos experience was also incorporated within ESA and its industrial partners. How has ELSA contributed to maintaining and extending the four above mentioned components of Europe's leading role in space astrometry?

Maximizing the scientific return from Gaia data If the Gaia catalogue with its 1 billion sources — including high accuracy astrometry, photometry, and radial velocities for over 100 million sources — would land on one's desk today it is not obvious how to most efficiently exploit this huge data set. Creative thinking and advance preparation is required in order to be ready to apply novel and efficient data analysis methods to the Gaia results. Moreover, the unprecedented levels of accuracy make it essential to think about possible complications in the interpretation of the data. Eight of the ELSA research projects were directly relevant to these areas. The work described by Váradi makes a strong case for publishing per-CCD photometry for the (short-period) variable stars observed by Gaia, and illustrates how the survey requirements evolve in response to preparatory research. Re Fiorentin provides an excellent example of how one can do current science as well as prepare for the Gaia data by analyzing the combination of existing astrometric (GSC-II), photometric (SDSS), and spectroscopic surveys (RAVE). The works of Santoro and Saguner illustrate how Gaia has stimulated new theoretical research into stellar structure and atmospheres as well as preparatory ground-based observational campaigns, which can already be exploited scientifically. Further preparations for the scientific analysis of Gaia data are described in the contributions by Czekai and Belcheva which focus on the non-trivial question of how to use the Gaia data to study our galaxy or the Magellanic clouds as a whole. These works also strengthened the Gaia universe model (see contribution by Luri) leading to more reliable simulations of the sky for mission and scientific preparations. The investigations by Pasquato into the effects of star spots on the astrometry from Gaia highlight the importance of re-examining the established methods of interpreting observational data when the accuracies are pushed to the limit. Finally the research into inversion methods by Oskiewicz has stimulated much discussion about the way in which the results from Gaia should be transmitted (more on this topic below).

The next generation of space astrometry experts One of the central aims of ELSA was of course to transfer the expertise from the generation involved in the Hipparcos project to a new generation who will be involved in the preparation and running of the Gaia mission. The network has been very successful in this respect, not only by directly training a new generation of space astrometry experts but also by serving as a focal point for research in support of the Gaia mission preparations. This is most clearly the case in the areas of the astrometric solution and the radiation damage mitigation. The AGISLab package developed by Holl is an essential tool in the development of enhancements to the astrometric iterative

solution and will be used to predict the complicated behaviour of the astrometric errors and the correlations between them. The conjugate gradient solver for the iterative astrometric solution was first implemented and tried in AGISLab before it was transferred to AGIS. This led to a large improvement in the speed of the astrometric solution as described by Bombrun which in turn facilitates research into the properties of the solution itself. The efforts by Risquez resulted in an accurate dynamical model of the Gaia spacecraft attitude which can be used to furnish realistically simulated attitude data for mission preparations. During the mission such a tool can aid the understanding of effects seen in the attitude reconstructed from the observations (see also the contribution by Van Leeuwen). Finally, in the case of Gaia there is no practical possibility to have two independent consortia carry out the data processing, yet it remains important to verify of the reliability of the Gaia catalogue through independent checks. This task is made possible by the work described by Abbas which will lead to an independent astrometric data reduction for a subset of the Gaia sources.

An important problem for the Gaia mission that was identified already at the time the mission was conceived is the issue of radiation damage to Gaia's CCDs caused by Solar wind protons. This leads to increased charge transfer inefficiency in Gaia's detectors and will affect all the data collected by Gaia by causing systematic errors that have to be accounted for. Again, ELSA served as a focus for efforts to mitigate the effects of radiation damage. The work by Prod'homme will result in the most sophisticated model to date of the effects of radiation damage on the charge collection and read-out process in CCDs. The contribution by Weiler describes how this work has stimulated the development of fast analytical models to describe radiation damage effects. Such models will play a central role in the data processing for Gaia.

Strengthening the partnership with industry The demands of the Gaia mission are pushing the limits of what can be achieved with conventional CCD technology and input from industrial partners has proved essential in the studies of radiation damage mitigation. The supplier of Gaia's CCDs, e2v, supported with their expertise the development of microscopic models of the electron distribution within a Gaia CCD pixel (work by G. Seabroke at Open University) which led to much improved modelling at the pixel level (see contribution by Prod'homme). The modelling work and the development of the radiation damage mitigation scheme for Gaia also relied heavily on the laboratory experiments that EADS-Astrium carried out with irradiated Gaia CCDs (see contribution by Pasquier). In turn the industrial partners were pushed by the constant questioning from the scientist to enhance their own understanding of radiation damaged CCDs. The new knowledge on CCDs was absorbed by ESA as the facilitating partner and this will certainly be of great benefit to future European space missions.

Networking and bringing in new expertise The opening and closing conferences of the ELSA network were aimed at bringing together the scientist that will use the Gaia data and the community that will produce the data. Where the

opening conference served to provide the ELSA fellows with the scientific motivation for their work, the conference of which this volume forms the proceedings served to show the European astronomical community how the Gaia data will be produced. I was pleased to hear an astronomer not involved in Gaia state; “I’m convinced I came to the right conference!”. These important contacts between ‘user’ and ‘producer’ were also fostered within the ELSA network, for example through the use of AGISLab in the study of Gaia’s capabilities with respect to variable stars.

Lastly, the ELSA network also successfully brought much needed outside expertise into the astronomical community. Examples are the engineering expertise of Prod’homme and the industrial partners, the mathematical expertise of Bombrun and the knowledge of high performance computing that is brought in through the work described by Fries in this volume.

2 Future proofing the Gaia data

Gaia will provide an unprecedented stereoscopic map of our Milky Way and the nearby universe. The catalogue will contain over 1 billion stars, $\sim 300\,000$ solar system objects, millions of galaxies, $\sim 500\,000$ quasars and thousands of exoplanets. For all these objects accurate astrometry, photometry, and (for a subset) spectroscopy will be available as ‘basic’ data. In addition the classification, variability characterization, and astrophysical parameters of each object will be provided. When this catalogue is ‘finished’ around 2020 and combined with other large sky surveys it will become *the* astronomical data resource for decades thereafter, representing a tremendous discovery potential.

However, I strongly believe that the true potential of the Gaia data can only be unlocked if we take an ambitious and innovative approach to data publication and access, including the provision of advanced data analysis tools. This means that we should not plan the catalogue publication based on what we can image is possible with current resources but rather base ourselves on what is possible after 2020. I therefore advocate the following guidelines:

Publish early and publish often The experience from the current large sky surveys, notably SDSS and RAVE, has shown that early and regular releases of the data are a very successful approach to survey publication. As pointed out in the contribution by Juric, the astronomical community very much appreciates and makes heavy use of the early releases (even if they are not as polished as one would like); the survey producers themselves benefit from immediate user feedback allowing them to correct important errors early on; it enables the rapid reaction by the community to new discoveries, and will facilitate synergies between Gaia and other projects. In this context it is worth keeping mind the enormous synergy possible between Gaia, LSST and Pan-STARRS, where especially in the case of LSST there is a smooth connection to the Gaia survey in terms of the astrometric and photometric accuracies achieved. The goal should thus be to set

an ambitious publication schedule with a first Gaia data release foreseen as soon as the sky has been surveyed once and an all-sky catalogue of positions, and broad-band photometry can be released (G , G_{BP} , G_{RP}). Such a trivial sounding data release (no parallaxes, motions, or detailed astrophysical characterization yet) will in fact constitute the highest spatial resolution all-sky map ever produced and I am convinced that it will lead to exciting discoveries. Such a release would in addition greatly enhance target selection for surveys that specifically aim at complementing Gaia with, for example, high resolution spectroscopy for chemical abundance determinations. This release should be followed with regular releases containing ever more, more complex, and better data.

Keep raw data, calibration data, and processing software available The contribution by Van Leeuwen shows how better insights into the attitude modelling for Hipparcos combined with present-day computing power enabled a higher quality re-processing of the entire Hipparcos data set. This resulting new version of the Hipparcos catalogue features very much reduced error correlations and improved astrometric accuracies (by up to a factor of 4) for the bright stars. This is the best illustration of the fact that the raw Gaia data, all the calibration data, and the processing software should be stored such that they are permanently accessible and readable, just as the catalogue itself will be. It is in fact a prerequisite for the next guideline.

Facilitate (re-) processing of the (raw) data Already in the case of Hipparcos there are numerous examples of the re-processing of the data, notably to improve the astrometry of binaries and very red giant stars. Other examples include the re-processing of intermediate data for groups of stars in order to derive a common radial velocity or parallax, the re-processing of data for objects that are discovered or confirmed to be binaries following a data release, or the re-determination of astrophysical parameters for stars following improvements in atmosphere modelling. In principle also for Gaia the re-processing of *all* the raw data might be warranted at some point in the future. In addition to the re-processing of the data the Gaia archive should also facilitate very complex operations on large chunks of the catalogue (say an all-sky search for stellar streams). Both these aims may be best served by implementing the idea of ‘bringing the processing to the data’ by offering users a virtual machine at the data centre hosting the Gaia archive. On this machine one could code whatever analysis or processing algorithm is called for and run it in a way specified by the user.

Make the archive ‘live’ A concept closely related to the previous item is that of making the Gaia data archive a ‘living entity’. By this I mean that it should be possible to incorporate new information into the catalogue. Examples are complementary ground-based spectroscopy, updated classifications or parameterizations of stars based on independent information, better distance estimates for faint stars, etc. In addition the Gaia archive should seamlessly integrate with other large sky

surveys including ones not foreseen at the time of the Gaia data publication. As an example, it should be possible to query the catalogue for sources brighter and fainter than the $G = 20$ survey limit of Gaia, where behind the scenes the work is done to combine Gaia and, for example, LSST data.

Don't publish a catalogue This guideline seems in complete contradiction to the discussion above but is meant to capture in a few words the ideas presented in the contribution by Hogg & Lang in this volume. I think serious efforts should be invested in their proposal to consider a 'catalogue' as only our best current model that explains all the raw data and to publish the data such that users can test their hypotheses (almost) against the raw image pixels. I do not expect that this approach will be possible anytime soon but it should not stop us from being ambitious and trying.

3 What about ELSA-II?

Is there a need for a follow-up to the ELSA research activities, i.e. investigations at the interface of astronomy, engineering, computer science and mathematics? I think the answer is yes and that there are in fact at least two different topics an 'ELSA-II' could focus on. The Gaia data will surely stimulate demands for future space astrometry missions that can open up new wavelength domains to precision astrometry, push the astrometric accuracy limits, or extend existing accuracies to much fainter stars. All these would require technological innovations to break the current scaling laws that would prevent us from simply building a Gaia++. A second and possibly more important avenue would be to pursue the ideas outlined in the previous section. Questions to investigate would be: how does one take care of the data curation for Gaia, including software and calibration data, such that the stored data are easily retrievable in the future? How do we best go about bringing the processing to the data or combining Gaia data with other archives in a transparent manner? How does one implement the testing of hypotheses against the raw data? Is this at all practically possible? Note that Pfenniger argues in his contribution that modelling the Galaxy may be best achieved through a very large particle number N -body simulation, possibly containing a particle for every star in the Galaxy. How does one decide for such models which is best? Do we convert these models to predictions of the Gaia pixels?

Although these research topics are oriented toward the longer term future they will generate many spin-offs that can be applied immediately to existing astronomical instruments, astronomical data, or in industry, thus maintaining and extending European Leadership in Space Astrometry.

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